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Development of a Watt-level gamma-ray source based on high-repetition-rate inverse Compton scattering

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ABSTRACT

A high-brilliance ($\sim 10^{22}$ photon s^{-1} mm^{-2} mrad^{-2}/0.1%) gamma-ray source experiment is currently being planned at Fermilab ($E_\gamma \simeq 1.1$ MeV). The source implements a high-repetition-rate inverse Compton scattering by colliding electron bunches formed in a ~300-MeV superconducting linac with a high-intensity laser pulse. This paper describes the design rationale along with some of technical challenges associated to producing high-repetition-rate collision. The expected performances of the gamma-ray source are also presented.

1. Introduction

High-flux, quasi-monochromatic, γ-ray sources could have widespread range of applications including in Nuclear Astrophysics, Elementary Particle Physics and Homeland security. In the later class of application, developing compact gamma-ray source capable of producing large flux could enable the rapid screening of cargos for fissile material detection. The need for monochromatic γ rays along with the requirement for a small-footprint source have motivated the exploration of particle-accelerator-based sources employing inverse Compton scattering (ICS) [1,2]. This development path is further supported by the increasing number of compact GeV-class electron sources based on laser-plasma wakefield accelerators (LPAs) available at various laboratories worldwide [3]. LPAs have so far been employed to generate γ rays with impressive brilliance but with restricted photon flux due to their low operating frequencies (typically 10 Hz) limited by the current solid-state-laser technologies [4,5]. Such a limitation of the LPAs is currently being addressed by several groups while the development of high-repetition rate interaction region could be performed at available state-of-the-art linear accelerators. Based on this observation, a collaboration between Fermilab, Northern Illinois University and RadiaBeam LLC is currently designing an experiment aimed at demonstrating high-repetition-rate ICS using the Fermilab Accelerator Science & Technology (FAST) facility based on a superconducting linear accelerator [6]. The present paper summarizes the design rationale and expected performances of the source under design.

2. Overview of the γ-ray source

Fig. 1 provides an overview of the source concept to be driven by the 300-MeV electron beam available at the FAST facility. In brief the electron bunches are produced via photoemission from a semiconductor photocathode located in a $1+\frac{1}{2}$-cell radiofrequency (RF) gun. The bunches are photoemitted by impinging an ultraviolet (UV) laser pulse obtained via frequency quadrupling of an amplified infrared (IR) laser pulse ($\lambda = 1053$ nm) produced from a Nd:YLF laser system. The formed bunches are further accelerated by two TESLA-type superconducting RF (SRF) cavities. The RF gun and cavities operate at 1.3 GHz and are capable of forming 1-ms bunch trains at 5-Hz frequency and containing up to 3000 bunches (corresponding to a 3-MHz bunch frequency). The 50 MeV beam can be manipulated and diagnosed before injection in an international-linear-collider- (ILC) type accelerating cryomodule. The cryomodule incorporates 8 SRF cavities with demonstrated average accelerating gradient of $\overline{G} \simeq 31.5$ MeV/m resulting in a maximum beam energy of ~300 MeV. The beam is further transported along a ~70 m beamline and finally directed to the

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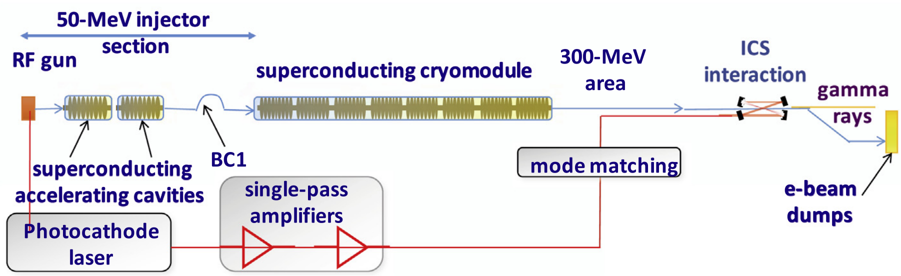

Fig. 1. Overview of the γ-ray source under consideration at the FAST facility. The "BC1" and "ICS" labels respectively refer to the bunch compressor and inverse-Compton scattering.

ICS interaction point (IP). Downstream of the IP, the electron beam is then sent to a high-power beam dump.

The laser pulse used in the ICS interaction is derived from the photocathode laser system. The unspent IR laser energy downstream of the IR-to-UV conversion process is conditioned, further amplified, and directed to a passive coherent enhancement cavity for final amplification. The laser pulses collides head-on with the electron bunches with a collision frequency of 3 MHz within the 1-ms train thereby yielding γ-ray pulses with similar format. The energy of the backscattered γ-ray photon is $E_s \simeq \hbar\omega_s$ where $\hbar$ is the reduced Planck's constant, and the upshifted backscattered-photon frequency is $\omega_s(\theta) = \frac{4\gamma^2\omega_l}{1+a_0^2/2+\gamma^2\theta^2}$,with $\hbar\omega_l \simeq 1.2$ eV and a_0 being respectively the laser photon energy and normalized potential, and γ the electron-beam Lorentz factor. The angle θ is the direction of observation referenced to the electron-beam direction. Therefore the 300-MeV beam available at FAST will support the generation of γ rays with $E_s \leqslant 1.5$ MeV. Considering a laser pulse energy $\mathcal{E}_l \sim 0.5$ J and a focused transverse size $\sigma_l \simeq 30$ µm, we obtain $a_0^2/2 \simeq 7.6 \times 10^{-3} \ll 1$ thereby confirming that nonlinear effects are insignificant for our operating parameters. Owing to its narrow bandwidth ($\delta\lambda \sim 0.2$ nm) the laser transform-limited rms pulse duration is 3 ps close to the measured value of 3.8 ps.

3. Expected performances

Applications of γ rays generally require high photon flux, narrow spectral bandwidth and high brilliance. The brilliance can be expressed as a function of the laser and electron-beams parameters [7] as

$$\mathcal{B}_s \propto \frac{N_l}{\sigma_l^2}\gamma^2\frac{N_e}{\tau_e\varepsilon_\perp^2}, \quad (1)$$

where N_l (resp. N_e) are the number of photons (resp. electron) in the laser pulse (resp. electron bunch), τ_e the electron-bunch duration and $\varepsilon_\perp$ its normalized transverse emittance (the electron beam and laser pulse are cylindrically symmetric). Likewise, the backscattered-photon dose N_s and relative spectral bandwidth of the scattered pulse $\delta\omega_s/\omega_s$ can be respectively parameterized as

$$N_s \approx \frac{N_e N_l \sigma_T}{2\pi(\sigma_e^2+\sigma_l^2)}, \text{ and } \frac{\sigma_{\omega_s}}{\omega_s} \approx 2\frac{\varepsilon_\perp^2}{\sigma_e^2}, \quad (2)$$

where σ_e is the electron-beam transverse rms size, σ_T the Thompson's cross section and $\hbar\sigma_{\omega_s}$ is the rms spectral spread of the backscattered radiation. Other sources contributing to $\sigma_{\omega_s}/\omega_s$ includes the laser spectral bandwidth, the laser divergence (diffraction), and electron beam's fractional momentum spread. The cumulative contribution of these effects is found to be negligible (~0.2%) for our operating regime.

We modeled the ICS process using the program COMPTON [8] which provides a 3D treatment of the laser-electron instruction in the time and frequency domains. The software also includes the nonlinear corrections to the Thompson cross section to correctly account for the electron recoil at the time scale of the interaction process. To gain further confidence in our modeling, we also employed the program CAIN [9] which is based on the more general Klein-Nishina cross-section for Compton-scattering process and consequently accounts for the quantum-electrodynamical (QED) effects. In our case, taking $\gamma \approx 500$, we find that the laser photon energy in electron-beam frame verifies $2\hbar\gamma\omega_l \approx 0.6$ keV $\ll m_e c^2 = 511$ keV (where $m_e c^2$ is the electron's rest mass) so that QED effects are expected to be insignificant. The codes COMPTON and CAIN were benchmarked and found to be in reasonable agreement over the considered range of parameters [10].

The COMPTON program was used to devise electron-beam and laser parameters such that scattered-pulse brightness, dose and bandwidth are optimized taking Eqs. 1 and 2 as guidelines. In practice only a small fraction of the scattered photons (i.e. the most energetic) are employed in front-end experiments. The selection is typically accomplished using transverse collimators exploiting the correlation between photon energy and angular spread (red shifting occurs off axis). The collimation results in the selection of a small fraction of the backscattered radiation. For example targeting $\sigma_{\omega_s}/\omega_s \simeq 0.5\%$ requires the collection angle to be $\theta_{col} \simeq \sqrt{\frac{\sigma_{\omega_s}}{2\omega_s}}\frac{1}{\gamma} \simeq 0.104$ mrad [7].

For each value of the electron bunch charge the normalized emittance is evaluated with the scaling relation $\varepsilon_\perp$ [µm] $\approx 2.94Q^{0.69}$[nC] determined from previous beam dynamics studies [11]. This value of emittance is then used to determine the electron beam transverse size by constraining $\frac{\varepsilon_\perp^2}{\sigma_e^2} = 2.5 \times 10^{-3}$; see also Eq. 2. The laser parameters are held constant and mimic the experimentally-achievable values. The number of scattered photons and associated energy bandwidth appear in Fig. 2 as functions of electron beam charge. Given the aforementioned constraint, a bandwidth $\hbar\sigma_{\omega_s} \simeq 6$ keV is maintained over the considered range of charges. The fraction of scattered photon within this bandwidth increases with charge and eventually saturate (for given our fixed set of laser parameters). Following Ref. [12] we evaluate the spectral density, defined as $\mathcal{S} \equiv \frac{N_{ph}}{\hbar\sigma_{\omega_s}\sigma_t}$. Considering the case of Q = 0.8 nC, we find $\mathcal{S} \simeq \frac{1.7\times10^5}{6.67}$ photons/s/eV per collision. Accounting for the capability of FAST to produce 15,000 bunches per second we get $\mathcal{S} \sim \mathcal{O}(10^5)$ photons/s/eV comparable with the value reported in [13]. Finally, it should be pointed out that only ~0.5% of the total number of backscattered photons are contained within the 0.6% relative bandwidth.

Table 1 compares the properties of the collimated and total backscattered radiation. The angular collimation leads to $\sigma_{\omega_s}/\omega_s \simeq 0.6\%$. It should be pointed out that the Table 1 provides the scattered pulse properties for a single-bunch collision. The brightness and dose should be multiplied by 15,000 in order to